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RESULTS FROM A NEW SEPARATION ALGORITHM FOR PLANETARY GEAR SYSTEM VIBRATION MEASUREMENTS

Marianne Mosher
NASA Ames Research Center
M.S. 269-3
Moffett Field, CA 94035-1000
mmosher@mail.arc.nasa.gov

ABSTRACT

Results are presented from a new algorithm developed for separating the vibration signals from a planetary gear system into separate signals attributable to each planet gear. From the separate signals, time synchronous average signals are produced for each planet gear and for the sun gear meshing with each planet gear. Assessments of the individual planet and sun gears can be made from these new vibration signals. These new separated signals match very well with noise-free synthetic data with and without characteristics indicative of faults. In a 3-planet system, distortions planted in synthetic signals are easily distinguished over a wide range of signal-to-noise (S/N) values. In an 8-planet system, distortions are easily detected for high S/N with degradation at low S/N. Spectra from separated signals from vibration measurements made in flight on the transmissions of OH-58C and AH1S helicopters are consistent with what would be expected based upon the transmission geometries.

Keywords: *Planetary gear system, Signal decomposition, Synthetic data, Helicopter, Vibration*

INTRODUCTION

Condition based maintenance and damage detection can reduce the cost and improve the reliability of machines. For transmissions in aircraft, vibration and oil debris monitoring are the main techniques for monitoring gear condition. Monitoring of overall vibration levels and oil debris yield general indication of condition. More detailed vibration analysis yields more accuracy and more specific condition information such as which component or components are degrading. For planetary gear systems, the vibration analysis is made more difficult by complexities in the vibration signal.

In this paper, the term planetary gear system refers to the compound gear systems with planet gears between a center sun gear and an outer ring gear, with the ring gear fixed and not rotating. The individual planet gears are connected through a carrier to the output of the gear system. Both planet/sun and planet/ring meshing produce vibrations.

Planetary gear systems (Figure 1) provide coaxial gear reductions and are useful for machinery with high power requirements. All helicopter transmissions contain one or more planetary gear systems in the speed reduction between the engine and rotor. Planetary gears commonly occur in the transmissions of helicopters, automobiles and trucks. Other uses include cranes, winches, wind turbines, pumps, robots and elevators.

Figure 1: A Planetary gear system. Courtesy of Mechanical Components Branch, NASA Glenn Research Center.

An understanding of vibration spectra is very useful for any gear fault detection scheme based upon vibration measurements. The vibration produced by planetary gear systems is more complex than the vibration produced by simple gear pairs. Most vibration energy produced by a simple pair of gears goes into the gear mesh frequency and its integer harmonics with some energy occurring at the shaft-order sidebands of these gear mesh harmonics. As gears wear and collect damage, more energy is shifted into the sidebands. Many gear vibration metrics utilize this characteristic of the vibration to indicate damaged gears. The vibration measured from normal planetary gears contains significant energy in many sidebands of the gear mesh harmonics as first noted by Sternfeld [1] and again by Gu [2, 3]. McFadden [4] proposed a model of the vibration that predicts high spectral amplitudes at multiples of the planet passage frequency (number of planets times planet carrier revolution frequency), for planetary gears with evenly spaced planets. This model correctly predicts shifting of the strong signal from a gear mesh frequency to a sideband of the meshing frequency when the number of teeth on the ring gear is not an integer multiple of the number of planets. McNames [5] elaborated McFadden's model. Mosher [6] elaborates this model further showing the relation of the transfer function of vibration to transducer and extension to the case of uneven planet spacing. In the time domain, the vibration signal contains amplitude and frequency modulations not present in the vibration signal from a simple gear pair. In the frequency domain, the vibration signal contains many frequency components of high amplitude at multiples of the planet repetition frequency (frequency at which the planet spacing pattern repeats) and clustered as sidebands near the gear mesh harmonics.

The added complexity in the vibration signal from planetary gear systems invalidates the use of the various metrics developed [7-9] to test for faults in gear pairs. Planetary gear vibration signal separation schemes have been developed with reported success by McFadden [10-12], Forrester [13] and Samuel [14, 15] to enable the detection of faults in planetary gear systems. For separation, the signal attributed to each planet gear is assembled from parts of the measured signal when the planet gear is closest to the measurement transducer. These signal separation methods all require knowing the location in time when a planet gear passes closest to the measuring accelerometer. Planet passage detection by use of a carrier phase signal requires the use and maintenance of the reference phase angle. The separation becomes more difficult with larger numbers of planet gears. Unevenly spaced planet gears add more complexity to the signal separation task.

In an alternative approach to monitoring planetary gear systems, Keller [16] proposed modifications to many standard metrics for application to planetary systems. These modifications work by redefining the residual and difference signals based upon removal of the more complicated planetary frequency components and their sidebands instead of the gear mesh harmonics and their sidebands. This method will not work for planetary systems with close spacing of the sidebands such as systems with a small number of planet gears or unevenly spaced planet gears. In these cases the redefined difference and residual signals will have had too many frequency components removed.

In this paper, the synthetic vibration model and the flight measurements will be described, followed by results from signal separation of the synthetic model data and the flight measurements. The accuracy of the new separation method is demonstrated on synthetic data. The time synchronous average signals of individual components in noise-free, synthetic data are compared to averages constructed from the separation of the total synthetic signal into parts attributable to individual gear meshing. The usefulness of the new separation algorithm is investigated on synthetic data with noise and simulated faults by comparing the values of a fault detection metric applied to time synchronous averages of both the original component synthetic faults and the averages made from the separation. Spectra from the time synchronous averages of the separated signals from vibration measurements made in flight on two helicopters are examined for consistency with expected characteristics of the component signals. This paper deals with the results from a new signal separation algorithm, it does not investigate the method of finding faults on the separate component signals.

PLANETARY GEAR SEPARATION

The planetary gear separation is done by an inversion of a model of the combined vibration signals from the components. It differs from previously published methods [10-15].

SYNTHETIC VIBRATION DATA MODEL

By working with synthetic data, the signal separation algorithm can be tested for accuracy with ideal signals and signals modeling faults. The accuracy of the algorithm can not be tested with vibrations measurements from flight or test rig because the component vibrations are not know for a real planetary gear transmission. Synthetic vibration signals are constructed from a kinematic model. In its simplest form, the model is the sum of amplitude-modulated, periodic planet gear mesh signals. The periodic signal contains frequency components at the gear mesh harmonics and represents the vibration at the planet gear mesh. The amplitude modulation models the transfer function from the planet mesh to the transducer as the planet gears revolve around the sun gear, producing the largest amplitude vibration when the planet gear is closest to the transducer. Adding Gaussian noise and amplitude variation among planet signals increases the complexity of the basic signal. Gear damage is modeled by local amplitude and phase modulation in the periodic gear mesh signal, repeated at either the planet gear or sun gear rotation period. Mosher [6] contains more details of the model for synthetic vibration data.

Models are made for the OH58A planetary gear system and the AH1S upper planetary gear system. With only three planet gears, the OH58A transmission is expected to provide the easiest signal to decompose into individual planet and sun signals. With eight planet gears, the AH1S poses a more significant challenge. Table 1 contains basic geometric information on the planetary gear systems considered in this study. All synthetic models of planetary gear vibration are constructed to be 200 carrier rotations long. On the OH58A, time synchronous averages of the planet gear are made of 27 rotations of the planet gear for the original signal and approximately 27 data points from the decomposition. This creates 20 averages of the original signal and 5 averages of the decomposed signal. The sun gear averages are made from 35 rotations to create 20 averages of the original signal and 5 averages of the decomposition. On the AH1S, time synchronous averages of the planet gear vibration are constructed from 57 rotations of the planet gear for the original signal and approximately 57 data points from the decomposition. This creates 13 averages of the original signal and 2 averages of the separated signal. The sun gear averages are made from 35 rotations to create 13 averages of the original signal and 2 averages of the decomposition.

To demonstrate the capability of the separation algorithm, time synchronous averages will be compared of planet and sun gear signals before they are combined into the total signal with averages constructed from the decomposed signals. When noise is added to the signals, this direct comparison is no longer appropriate. The gear fault metric FM4 [7] will be used to compare original with reconstructed signals for the synthetic signals containing Gaussian random noise. This metric is now an indicator of the ability to find planted distortions that mimic faults when using the separation algorithm. The metric FM4 is the normalized kurtosis of the time synchronous average signal with the regular components removed from the signal, also referred to as the "difference signal". The regular components are the frequencies corresponding to 1 and 2 per rotation of the gear, the gear mesh integer harmonics and the 1 per rotation sidebands of the gear mesh harmonics. In theory, this difference signal will contain only noise for a gear in good condition. With only noise, the expected value of the normalized kurtosis of the difference is 3. In theory, when the gear contains localized damage, the kurtosis of the difference signal increases above 3. To evaluate the separation algorithm, distortion will be added to the gear in the original signal which is identifiable with FM4. The value of FM4 will be calculated on the various components, planet gears and sun gear, derived from the separated signal. If the separation algorithm works well, the component containing the distortion will be identifiable by the FM4 marker.

Table 1: Transmissions used in study

	OH58A	AH1S upper	OH58C
Number planets	3	8	4
Number teeth per planet	35	31	35
Number teeth on ring gear	99	119	99
Number teeth on sun gear	27	57	27

FLIGHT MEASUREMENTS

NASA Ames Research Center has been measuring vibration of helicopter transmissions in flight tests since 1998. Ames' researchers tested the AH-1S helicopter in 1998, 1999 and 2001; and the OH-58C helicopter in 2000, 2001, 2003 and 2004. The earlier flights, 1998 through 2000, were done with a series of controlled flight maneuvers (see Huff [17, 18] for details). In the later flights [19], data were collected at periodic intervals throughout a flight, capturing data from whatever flight condition the helicopter was in at the time.

The AH-1S was instrumented with two tri-axial accelerometers on the transmission cover, one near the upper planetary ring gear and the other near the lower planetary ring gear. The OH-58C was instrumented with one tri-axial accelerometer and three single axis accelerometers, all mounted on the casing around the ring gear. On both helicopters, torque was measured by calibrating the oil pressure and the main rotor shaft was instrumented with a 1/rev signal generator. Vibration data, oil pressure for torque and a 1/rev signal were collected with a pc-based digitized system on board the aircraft. The antialiasing filter was set to 18 kHz and sample rate was 50 kHz.

In this paper, data will be used from the upper planetary gear in the AH1S from a level flight condition in 1999. Data will be used from the OH58C in a level flight condition in 2000.

In the case of data analyzed from flight measurements, the state of the components is assumed to be good. No problems with the transmissions have been identified years after the measurements. Spectra of the time synchronous averages of the component signals derived from the separation algorithm will be shown. The 1/rev signal is on the output rotor shaft, so it gives a pulse once per rotation of the planet carrier. This pulse lines up for synchronous averaging of the carrier rotation. For synchronous averaging of all other gears, the gear rotation angle is interpolated from the 1/rev signal. If the signals contain energy mainly of gear mesh harmonics, then the signals are consistent with a good separation. If the signals contain much energy in sidebands around the gear mesh harmonics, then the separation algorithm is assumed to have failed.

SYNTHETIC VIBRATION DATA RESULTS

Since the component signals are not known for measured vibration of planetary gears, the accuracy of the algorithm will be checked with synthetic data constructed from known components. The first example consists of the simplest case for the 3-planet OH58A transmission model. The gear meshing vibration is represented with a periodic signal consisting of energy at the first 7 gear mesh harmonics and no variations to represent teeth differences, gear differences or faults and no noise. The algorithm does an excellent job at reconstructing the planet gear signals and the sun gear signal as can be seen in Figure 2 and Figure 3 respectively. Note that both the signals associated with the planet gear and the sun gear is recovered very well. Quantitative measures: correlation coefficient, rms error normalized by rms signal and ratio of rms decomposition to rms of original signal all yield excellent values as shown in Table 2.

The second example contains some distortions to sun gear signal, larger amplitude by a factor of 1.2 for the first planet gear signal and no noise. The quantitative comparisons shown in Table 3 are slighted degraded from the first example, and still excellent.

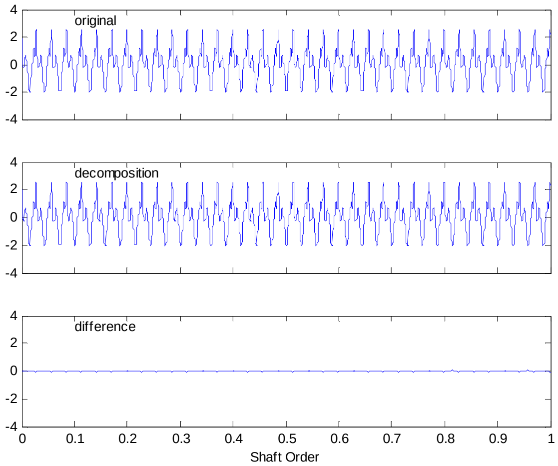

Figure 2: Time synchronous average of one rotation of planet 1 for original synthetic signal, decomposition from complete planetary gear signal and difference. No distortions, no noise.

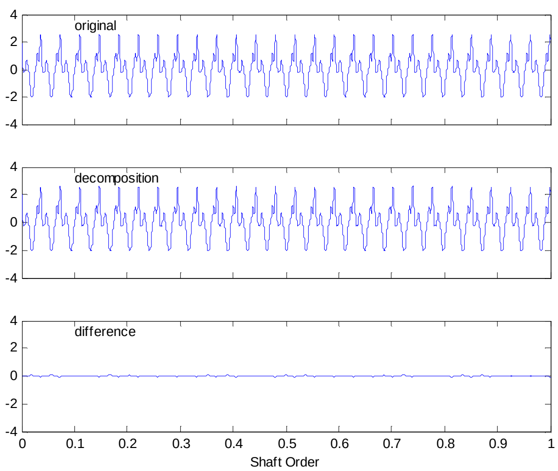

Figure 3: Time synchronous average of one rotation of sun gear for original synthetic signal, decomposition from complete planetary gear signal (based upon interaction with planet 1) and difference. No distortions, no noise.

All following examples contain noise and distortions that mimic faults on either a planet gear or the sun gear. The distortions that mimic faults are designed to be identifiable with the fault metric FM4. With the addition of noise the quantitative measures, correlation coefficient, rms error and rms ratio, are not good indicators of the accuracy of the decomposition algorithm. This is because the time synchronous averages of the original signals and the decomposition signals are constructed from different pieces of signal and thus the noise component differs in the two cases. The metric FM4 will now be used to compare time synchronous averages of the original signals with the decomposition signals for all averages made for an example case. The third and forth examples both contain a S/N = 7.2 dB with a distortion mimicking a gear fault on planet number one and a distortion mimicking a sun gear fault respectively. In the signals where no distortions were introduced, the level of FM4 is close to 3, the expected value for no fault. Where distortions mimicking faults are placed, the level of FM4 is increased above the nominal value of 3 for both the original time synchronous averages and the time synchronous averages constructed from the decomposition signals, as seen in Table 4.

Table 2: Comparison between original synthetic signal and decomposition for simple 3-planet case with no distortions and no noise.

	corr coef	rms error	rms ratio
Planet 1	1	0.0214	1.0214
Planet 2	1	0.0214	1.0214
Planet 3	1	0.0215	1.0215
Sun 1	0.99997	0.0219	1.0205
Sun 2	0.99997	0.0219	1.0205
Sun 3	0.99997	0.0219	1.0205

Table 3: Comparison between original synthetic signal and decomposition for simple 3-planet case with distortion on sun gear signal, larger amplitude by factor of 1.2 on planet # 1 gear signal and no noise.

	corr coef	rms error	rms ratio
Planet 1	0.99968	0.0276	1.0110
Planet 2	0.99974	0.0374	1.0292
Planet 3	0.99969	0.0367	1.0265
Sun 1	0.99998	0.0134	1.0114
Sun 2	0.99994	0.0278	1.0253
Sun 3	0.99992	0.0286	1.0255

Table 4: Comparisons of the damage metric FM4 for original synthetic signals and reconstructed signals from the planetary decomposition. S/N = 7.2 dB, 3-planet transmission.

	mean original FM4	Min original FM4	max original FM4	mean decomp FM4	min decomp FM4	max decomp FM4
planet 1 fault						
Planet 1	4.199	3.698	4.633	4.479	3.916	4.947
Planet 2	2.985	2.742	3.181	3.029	2.956	3.094
Planet 3	3.006	2.807	3.206	3.066	2.941	3.176
Sun 1	3.039	2.842	3.211	3.018	2.881	3.130
Sun 2	3.075	2.818	3.289	2.992	2.853	3.165
Sun 3	3.009	2.862	3.220	3.190	3.112	3.259
sun fault						
Planet 1	2.957	2.825	3.104	3.068	2.935	3.247
Planet 2	3.016	2.835	3.153	3.013	2.930	3.100
Planet 3	3.011	2.795	3.171	2.999	2.778	3.317
Sun 1	4.565	4.028	5.526	4.911	4.553	5.419
Sun 2	4.773	4.143	5.651	5.083	4.244	6.052
Sun 3	4.674	4.204	5.577	4.908	4.544	5.192

The next examples will look at the effect of increasing the noise level in example 3 with a distortion mimicking a fault on planet number 1. The amplitude of the distortion will also be increased; otherwise as the noise level increases the metric FM4 will not identify the distortion in the original synthetic signal. For S/N of 7.2, the amplitude of the distortion is 1.3 times the amplitude of the undistorted signal, for all other noise levels the amplitude of the distortion is 3 times the level of the undistorted signal. The levels of S/N in the original synthetic signal without averaging are 7.2, -12.8, -26.7 and -38.8 dB. The S/N level of 7.2 db is higher than is seen in flight measurements and the level of -38.8 is lower than what is typically seen in flight. The signals reconstructed from the planetary gear separation algorithm retain the distortion characteristic very well as measured by FM4 for all noise levels (Figure 4 to Figure 7). Values of FM4 from decomposed planet signals without distortions remain close to 3 and the values from planet signals with distortions remain high. The multiple measurements are shown in box plots. The box encloses values from the 25th to the 75th percentiles with a line indicating the median. Outliers are shown as crosses.

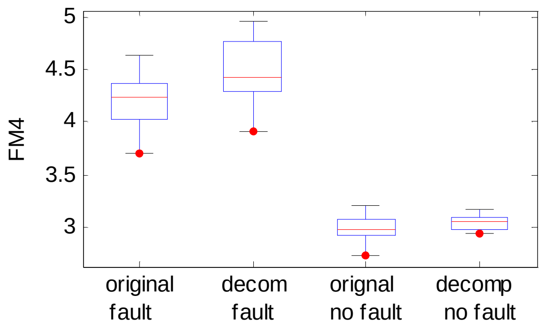

Figure 4: Fault metric (FM4) of time synchronous average for original planet signals used in creating synthetic data and decomposed plant signals for planet with simulated fault on left and without simulated fault on right. S/N = 7.2 dB, 3-planet transmission.

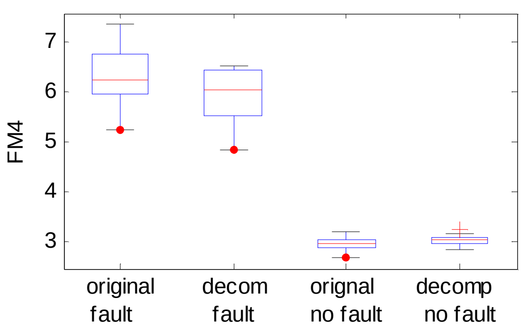

Figure 5: Fault metric (FM4) of time synchronous average for original planet signals used in creating synthetic data and decomposed plant signals for planet with and without simulated fault, S/N = -12.8 dB, 3-planet transmission.

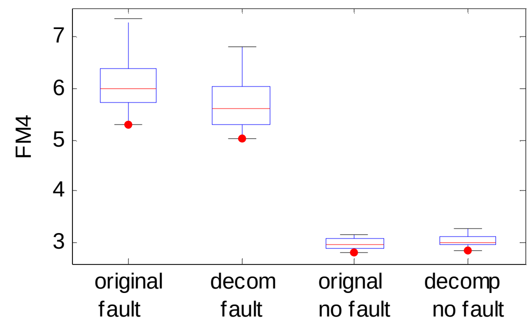

Figure 6: Fault metric (FM4) of time synchronous average for original planet signals used in creating synthetic data and decomposed plant signals for planet with and without simulated fault, S/N = -26.7 dB, 3-planet transmission.

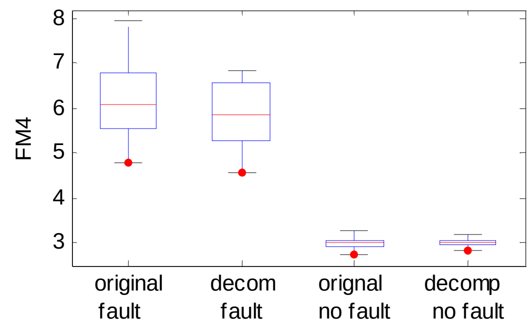

Figure 7: Fault metric (FM4) of time synchronous average for original planet signals used in creating synthetic data and decomposed plant signals for planet with and without simulated fault, S/N = -38.8 dB, 3-planet transmission.

With more planet gears it becomes more difficult to see the individual planet passages in measurements. With more planet gears in the system, the task of separating the signals becomes more difficult. The next examples contain eight planet gears and match the gear and tooth configuration of the AH1S upper planetary gear system. In the example with high S/N of 7.2 dB, the fault and no fault cases are still easily distinguished with the FM4 metric (see Figure 8). In the examples with S/N of -12.8 (Figure 9) and -26.7 dB (Figure 10), the ability to detect the distortion with the FM4 metric is clearly reduced. Some overlap now exists in the FM4 measures for the signals with and without distortions of the averages made from the decomposition signals.

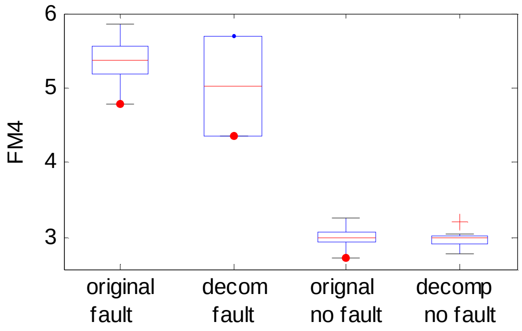

Figure 8: Fault metric (FM4) of time synchronous average for original planet signals used in creating synthetic data and decomposed plant signals for planet with and without simulated fault. S/N = 7.2 dB, 8-planet transmission.

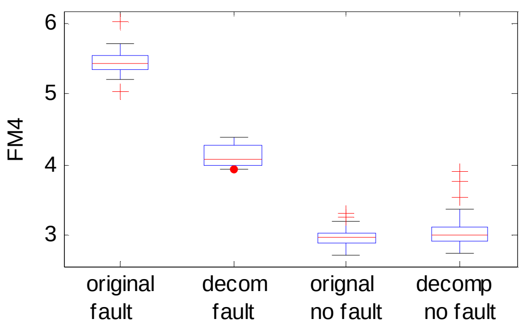

Figure 9: Fault metric (FM4) of time synchronous average for original planet signals used in creating synthetic data and decomposed plant signals for planet with and without simulated fault. S/N = -12.8 dB, 8-planet transmission.

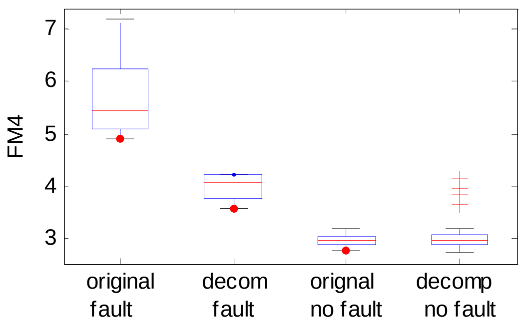

Figure 10: Fault metric (FM4) of time synchronous average for original planet signals used in creating synthetic data and decomposed plant signals for planet with and without simulated fault. S/N = -26.7 dB, 8-planet transmission.

FLIGHT VIBRATION DATA RESULTS

Vibration measurements from real transmissions are more complex than the synthetic data. The decomposition algorithm is applied to some measurements made in flight as part of the evaluation. The fist example consists of the 4-planet OH58C transmission. The spectrum from a time synchronous average of the original signal interpolated to a constant number of points per rotation shows energy at multiple sidebands of the gear mesh harmonics. Spectra containing the first five gear mesh harmonics are shown in Figure 11 for this original signal and for decomposed signals. The stars identify the frequency location of the spectral components expected for the planetary gear signal. Note that the frequencies are indexed according to shaft order or one rotation of the gear, and thus have different indices for the gear mesh harmonics depending upon the gear. After signal separation, the spectra for the reconstructed planet and sun gear show a greater concentration of the energy at the gear mesh harmonics and not at its sidebands. For the planet gear and sun gear, the stars identify the frequency location of the gear mesh harmonics. These spectra are consistent with a good decomposition, but do not guarantee one.

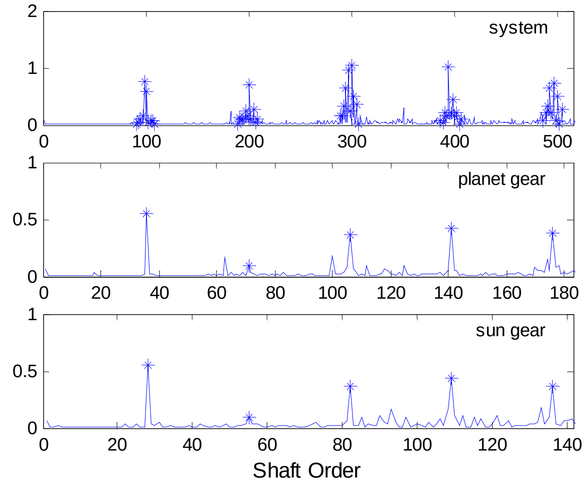

Figure 11: Flight data showing spectra of time synchronous averages from original measurement and decomposition for 4-planet OH58C transmission, S/N = -7.1.

The second flight example (Figure 12) is from the 8-planaet upper planetary gear in the AH1S transmission. In this example containing more planet gears and potentially more difficult to separate signal, the spectra from the decomposed signals are not quite as clean, especially for the sun gear. The extra frequency components near the third harmonic of the sun gear are believed to come from the lower planetary gear system. The sun gear is closer to the lower planetary gear system.

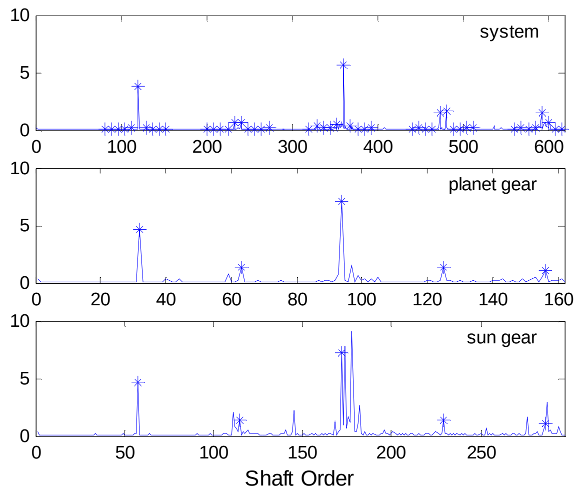

Figure 12: Flight data showing spectra of time synchronous averages from original measurement and decomposition for 8-planet AH1S transmission, S/N = -11.3.

CONCLUSION AND DISCUSSION

Examples of reconstructed sun gear and planet gear signals from a new signal separation algorithm were shown for synthetic data of 3-planet and 8-planet systems. Measured data from flights of a 4-planet OH58C and 8-planet AH1S transmissions were also separated. The following results were obtained:

1. For ideal 3-planet synthetic data, the reconstruction of signals identified with the planet gears and sun gear is excellent. The correlation coefficients are extremely close to 1 and relative errors are about 2%. The reconstruction remained excellent when a distortion was added to the sun gear signal and with one planet gear having larger amplitude.
2. With the addition of Gaussian random noise with S/N levels of 7.2, -12.8, -26.7 and -38.8, the addition of a distortion was easily identified with the metric FM4 in the reconstructions from the separated signals for the 3-planet synthetic signals.
3. For the 8-planet synthetic signals, the addition of noise degraded the identification of the distortion at the higher noise levels.
4. For signals measured in flight on an OH58C, the reconstructed planet and sun gear signals contain reasonable spectra consistent with correct signal separation.
5. For signals measured in flight of the upper planetary gear system in the AH1S, the spectra in the reconstructed signals is not quite as good as for the OH-58C. In particular, extra frequency components occur near the third gear mesh harmonic that probably arise from the lower planetary gear system.

More work is needed to evaluate this signal separation algorithm. The algorithm still needs to be systematically applied to the available flight measurements to ensure consistent results. More importantly, the algorithm needs to be applied to measurements with known damage to the gears. Collaboration is planned with researchers from NASA Glenn Research Center to evaluate this separation algorithm on upcoming tests of a planetary gear system with and without gear damage.

The author believes that damage detection techniques for gears needs to be improved before damage can be reliably assessed from vibration signals of planetary gear systems. The existing gear damage detection metrics are not sufficient. The author expects accurate anomaly detection schemes to be more reliable. Two examples of finding anomalies in gear vibration measurements are described in Samuel [14], Mosher [20] and Pryor [21].

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